CSE 30321 – Lecture 07-09 – In Class Example Handout

Part A: A Simple, MIPS-based Procedure:

Swap Procedure Example:

Let's write the MIPS code for the following statement (and function call):

```
if (A[i] > A [ i+1])            // $s0 = A
     swap (&A[i], &A[i+1])      // $t0 = 4*i
```

We will assume that:

- The address of A is contained in $s0 ($16)
- The index (4 x i) will be contained in $t0 ($8)

Answer:

The Caller:

```
        …
        // Calculate address of A(i)
        add     $s1, $s0, $t0           // $s1 ← address of array element i in $s1

        // Load data
        lw      $t2, 0($s1)             // load A(i) into temporary register $t2
        lw      $t3, 4($s1)             // load A(i+1) into temporary register $t3

        // Check condition
        ble     $t2, $t3, else          // is A(i) <= A(i+1)?  If so, don't swap

        // if >, fall through to here…
        addi    $a0, $t0, 0             // load address of x into argument register (i.e. A(i))
        addi    $a1, $t0, 4             // load address of y into argument register (i.e. A(i+1))

        // Call Swap function
        jal     swap                    // PC ← address of swap; $ra l $31 = PC + 4
else:
```

// Note that swap is "generic" – i.e. b/c of the way data is passed in, we do not assume the values
// to be swapped are in contiguous memory locations – so two distinct physical addresses are
// passed in

```
Swap:
        lw $t0, 0($a0)          // $t0 = mem(x) – use temporary register
        lw $t1 0($a1)           // $t1 = mem(y) – use temporary register
        sw 0($a0), $t1          // do swap
        sw 0($a1), $t0          // do swap
        jr $ra                  // $ra should have PC = PC + 4
                                // PC = PC + 4 should be the next address after jump to swap
```

Part B: Procedures with Callee Saving (old exam question):

Assume that you have written the following C code:

```
//--------------------------------------------------------------------
int   variable1   = 10;                   // global variable
int   variable2   = 20;                   // global variable
//--------------------------------------------------------------------
int main(void) {
      int i       = 1;                    // assigned to register s0
      int j       = 2;                    // assigned to register s1
      int k       = 3;                    // assigned to register a3
      int m;
      int n;

      m = addFourNumbers(i, j);

      n = i + j;                          // 1 + 2    = 3

      printf("m is %d\n", m);             // printf modifies no registers
      printf("n is %d\n", n);             // printf modifies no registers
      printf("k is %d\n", k);             // printf modifies no registers
}
//----------------------------------------------------------------------
int addFourNumbers(int x, int y) {
      int i;                              // assigned to register s0
      int j;                              // assigned to register s1
      int k;                              // assigned to register s2

      i     = x + y;                      // 1 + 2    = 3
      j     = variable1 + variable2;      // 10 + 20  = 30
      k     = i + j;                      // 3 + 30   = 33

      return k;
}
//----------------------------------------------------------------------

The output of the printf statements in main is: m is 33
                                                n is 3
                                                k is 3
```

Assume this program was compiled into MIPS assembly language with the register conventions described on Slide 12 of Lecture 07/08. Also, note that in the comments of the program, I have indicated that certain variables will be assigned to certain registers when this program is compiled and assembled. Using a callee calling convention, answer the questions below:

Q-i: Ideally, how many arguments to the function addFourNumbers must be saved on the stack?

0. By default, arguments should be copied into registers.

Q-ii: What (if anything) should the assembly language for main() do right before calling addFourNumbers?

Copy values of s registers into argument registers; save value of k (in $a3) onto the stack

Q-iii: What is the first thing that the assembly language for addFourNumbers should do upon entry into the function call?

Callee save the s registers

Q-iv: What is the value of register number 2 (i.e. 0010_2) after main completes (assuming there were no other function calls, no interrupts, no context switches, etc.)

33. Register 2 = v0. It should *not* have changed.
(different answer if you assume printf returns value)

Q-v: Does the return address register ($ra) need to be saved on the stack for this program? Justify your answer. (Assume main() does not return).

No – if no other procedures are called.

Part C: Procedures with Callee Saving (old exam question):

Assume you have the following C code:

```
int main(void) {
        int x = 10;                     # x maps to $s1
        int y = 20;                     # y maps to $s2
        int z = 30;                     # z maps to $s3

        int a;                          # a maps to $t0
        int b;                          # b maps to $t1
        int c;                          # c maps to $t2

        c = x + y;

        a = multiply(x, z);

        b = c + x;
}

int multiply(int a, int b) {
        int q;                          # q maps to $t0
        int z;              ■           # z maps to $t1

        q = add();
        z = a*b;              ▲

        return z;
}

int add() {
        int m = 5;                      # m maps to $t4
        int n = 4;                      # n maps to $t5
        int y;
        y = a + b;
        return y;
}
```

Assuming the MIPS calling convention, answer questions A-E. Note – no assembly code/machine instructions are required in your answers; simple explanations are sufficient.

Q-i: What, if anything must main() do before calling multiply?

- **Save $t2 to stack, needed upon return.**
- **Also, copy $s1 to $a0 and copy $s3 to $a1**

Q-ii: Does multiply need to save anything to the stack? If so, what?

- **$31**
- **The s registers associated with main()**
- **The argument registers passed into multiply before calling add()**

Q-iii: Assume that multiply returns its value to main() per the MIPS register convention. What machine instructions might we see at ▲ to completely facilitate the function return?

- **We have to copy the value in $t1 to $2.**
- **We would call a jal instruction**
- **We would adjust the stack pointer, restored saved registers.**

Q-iv: What line of code should the return address register point to at ▲?

- **b = c + x**

Other answers were considered correct based on stated assumptions.

Q-v: What line of code should the return address register point to at ■?

- **b = c + x**

Other answers were considered correct based on stated assumptions.

Part D: More Complex Example:

Let’s write the MIPS code for the following:

```
for(i=1; i<5; i++) {         int function(int, int) {     Assume:
  A(i) = B*d(i);               A(i) = A(i-1);             Addr. of A = $18
  if(d(i) >= e) {              e = A(i);                  Addr. of d = $19
    e = function(A,i);         return e;                  B = $20
  }                          }                            e = $21
}

                             (We pass in starting “address of A” and “i”)
```

Question/Comment	My Solution	Comment
1st, want to initialize loop variables. **What registers should we use, how should we do it?**	addi $16, $0, 1 addi $17, $0, 5	# Initialize i to 1 # Initialize $17 to 5 (in both cases, *saved* registers are used – we want this data available post function call)

2nd, calculate address of d(i) and load. **What kind of registers should we use?**	Loop: sll $8, $16, 2
	add $8, $19, $8
	lw $9, 0($8)
		# store i*4 in $8 (temp register OK)
		# add start of d to i*4 to get address of d(i)
		# load d(i) → needs to be in register to do math

Calculate B*d(i)	mult $10, $9, $20	# store result in temp to write back to memory

Calculate address of A(i)	sll $11, $16, 2
	add $11, $11, $18
	
	CANNOT do:
	add $11, $8, $18
		# Same as above
		
		# We overwrote
		# But, would have been better to save i*4
		Why? Lower CPI

Store result into A(i)	sw $10, 0($11)	# Store result into a(i)
Now, need to check whether or not d(i) >= e. **How? Assume no ble.**	slt $1, $9, $22 bne $0, $1, start again	# Check if $9 < $22 (i.e. d(i) < e) # Still OK to use $9 → not overwritten # (temp does not mean goes away immediately) # if d(i) < e, $1 = 1 # if d(i) >= e, $1 = 0 (and we want to call function) # (if $1 != 0, do not want to call function)

Given the above setup, what comes next? (Falls through to the next function call). **Assume argument registers, what setup code is needed?**	add $4, $18, $0
	add $5, $16, $0
	x: jal function
		# load address of (A) into an argument register
		# load i into an argument register
		# call function; $31 ← x + 4 (if x = PC of jal)

Finish rest of code: **What to do?** Copy return value to $21. Update counter, check counter. **Where is "start again" at?**	add $21, $0, $2 sa: addi $16, $16, 1 bne $16, $17, loop	# returned value reassigned to $21 # update i by 1 (array index) # if i < 5, loop A better way: Could make array index multiple of 4
Function Code		

Assume you will reference A(i-1) with lw … 0($x). **What 4 instruction sequence is required?**	func: subi $5, $5, 1
	sll $8, $5, $2
	add $9, $4, $8
	lw $10, 0($9)
		# subtract 1 from i
		# multiply i by 4 → note
		# add start of address to (i-1)
		# load A(i-1)

Finish up function.	sw $10, 4($9) add $2, $10, $0	# store A(i-1) in A(i) # put A(i-1) into return register ($2)
Return	jr $31	# PC = contents of $31

Part E: Nested Function Calls

```
int main(void) {
  i = 5;   # i = $16
  j = 6;   # j = $17
  k = foo1();
  j = j + 1;
}
```

```
foo1() {
  a = 17;   # a = $16
  b = 24;   # b = $17
  …
  foo2();
}
```

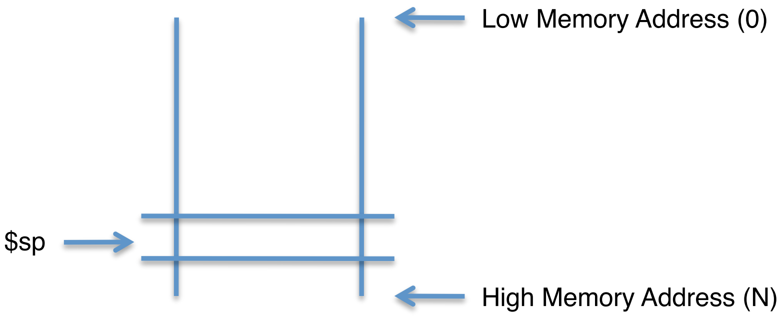
```
foo2() {
  x = 25; # x = $16
  y = 12; # y = $17
}
```

Let’s consider how we might use the stack to support these nested calls.

Question:
How do we make sure that data for i, j ($16, $17) is preserved here?

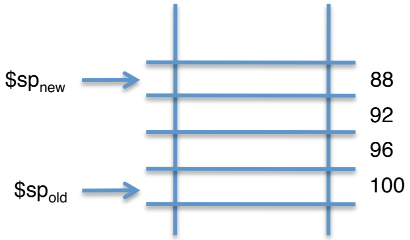
Answer:
Use a stack.

By convention, the stack grows up:



Let’s look at main():

- Assume we want to save $17 and $16
  - (we’ll use the stack pointer)
- Also, anything else we want to save?
  - $31 – if nested calls.
- How?
  - subi $sp, $sp, 12 # make space for 3 data words
  - Example: assume $sp = 100, therefore $sp = 100 – 12 = 88
- Then, store results:
  - sw 8($sp), $16 # address: 8 + $sp = 8 + 88 = 96
  - sw 4($sp), $17 # address: 4 + $sp = 4 + 88 = 92
  - sw 0($sp), $31 # address: 0 + $sp = 0 + 88 = 88



Now, in Foo1() … assume A and B are needed past Foo2() … how do we save them?

- We can do the same as before
  - Update $sp by 12 and save

Similarly, can do the same for Foo2()

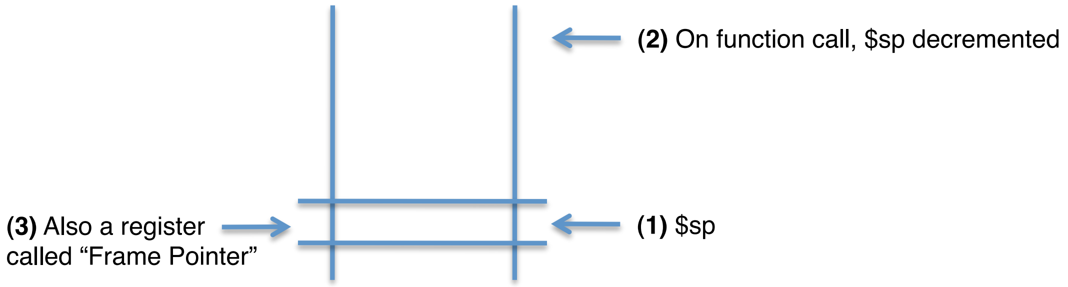
Now, assume that we are *returning* from Foo1() to main(). What do we do?

- The stack pointer should equal the value before the Foo1() call (i.e. 88)

```
lw $31, 0($sp)     # $31 ← memory(0 + 88)     (LIFO)
lw $17, 4($sp)     # $17 ← memory(4 + 88)
lw $16, 8($sp)     # $16 ← memory(8 + 88)
```

Finally, update $sp: addi $sp, $sp, 12 ($sp now = 100 again)

Let's talk about the Frame Pointer too:

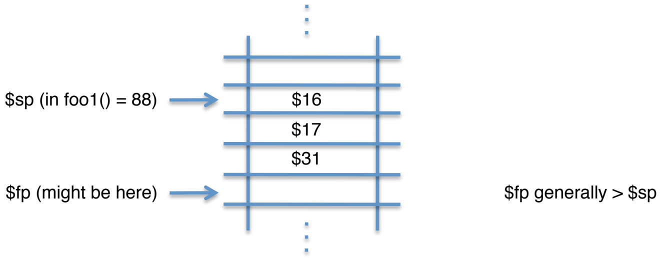


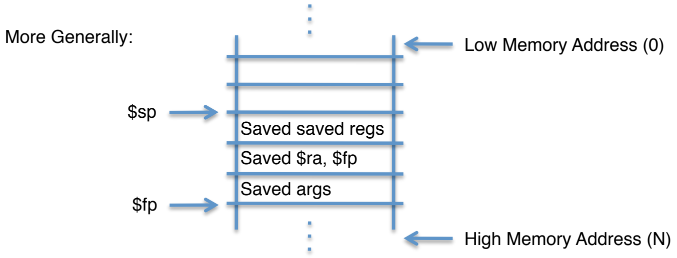
$fp (frame pointer) points to the “beginning of the stack” (ish) – or the first word in frame of a procedure

Why use a $fp?

- Stack used to store variables local to procedure that may not fit into registers
- $sp can change during procedure (e.g. as just seen)
    - Results in different offsets that may make procedure harder to understand
- $fp is stable base register for local memory references

For example:

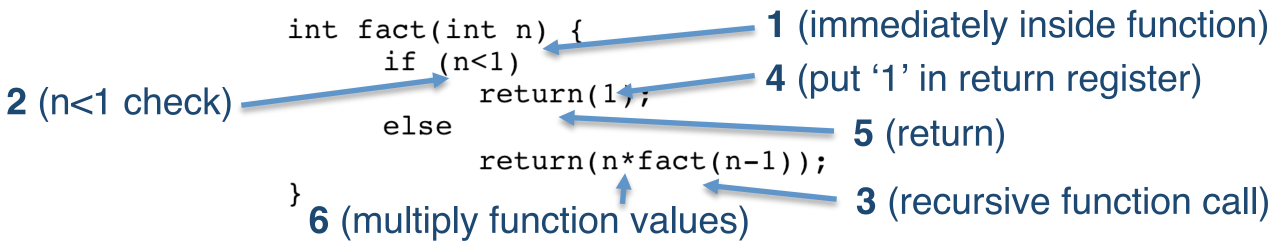




-Therefore procedure might reference extra function argument as 0($fp)
-What if 2 saved arguments? What next?
-With this convention: lw $t0, 4($fp)

Because $sp can change dynamically, often easier/intuitive to reference extra arguments via stable $fp – although can use $sp with a little extra math

Part F: Recursive Function Calls



```
int fact(int n) {
      if (n<1)
            return(1);
      else
            return(n*fact(n-1));
}
```

Let’s consider how we might use the stack to support these nested calls. We’ll also make use of the frame pointer ($fp).

Code Section #	Address	Label	MIPS Instruction	Comments
1	0	Fact:	subi $sp, $sp, 12	Make room for 3 pieces of data on the stack; $fp, $sp, and 1 local argument
	4		sw 8($sp), $ra	If $sp = 88, M(88 + 8) ← value of $ra
	8		sw 4($sp), $fp	If $sp = 88, M(88 + 4) ← value of $fp
	12		subi $fp, $fp, 12	Update the frame pointer
2	16		bgtz $a0, L2	If N > 0 (i.e. not < 1) we’re not done → we assume N is in $a0
4	20		addi $v0, $0, 1	We eventually finish and want to return 1, therefore put 1 in return register
	24		j L1	Jump to return code
3	28	L2:	sw $a0, 0($fp)	Save argument N to stack (we’ll need it when we return)
	32		subi $a0, $a0, 1	Decrement N (N = N – 1), put result in $a0
	36		jal Fact	Call Factorial() again
6	40		lw $t0, 0($f0)	Load N (saved at *** to stack)
	44		mult $v0, $v0, $t0	Store result in $v0
5	48	L1:	lw $ra, 8($sp)	Restore return address
	52		lw $fp, 4($sp)	Restore frame pointer
	56		addi $sp, $sp, 12	Pop stack
	60		jr $ra	Return from factorial

4 N > 1?

5 If so, store old value of N (data that needs to be saved), ref $fp

8a More of the same

9 $ra is in factorial

10a More of the same

Code Trace:

1st Call to Factorial

Addr	What Happens
0	$sp = $sp-12; $sp ← 100
4	M(100+8) = M(108) ← $ra
8	M(100+4) = M(104) ← $fp
12	$fp = $fp-12; $fp ← 112
16	2 is greater than 0
28	M($fp / 112) ← N (store #)
32	N = N-1 (new arg = 1)
36	jal Fact ($ra = 40_{10})

2nd Call to Factorial

Addr	What Happens
0	$sp = $sp-12; $sp ← 88
4	M(96) ← $ra ($ra=40)
8	M(92) ← $fp ($fp =112)
12	$fp = $fp-12; $fp ← 100
16	1 is greater than 0
28	M($fp / 100) ← N (store #)
32	N = N-1 (new arg = 0)
36	jal Fact ($ra = 40_{10})

3rd Call to Factorial

Addr	What Happens
0	$sp = $sp-12; $sp ← 76
4	M(84) ← $ra ($ra=40)
8	M(80) ← $fp ($fp =100)
12	$fp = $fp-12; $fp ← 88
16	0 is NOT greater than 0
	(start to return)

10c Now meet exit criteria

6, 7 Calculate number to pass to function, call factorial again

12 Restore saved variable, calculate value to return: $v0 from old call, stored N; calculated value becomes $v0

Return from 3rd Call

Addr	What Happens
20	addi $v0, $0, 1 (return 1)
24	j L1
48	$ra ← M($sp+8) ← M(84) $ra ← 40
52	$fp ← M($sp+4) ← M(80) $fp ← 100
56	$sp = 76+12; $sp ← 88 (pop stack)
60	jr $ra implies that PC ← 40

Return from 2nd Call

Addr	What Happens
40	lw $t0, 0($fp); $t0 ← M(100); $t0 ← 1
44	$v0 ← 1x1 $v0 = return address reg.
48	$ra ← M($sp+8) ← M(96) $ra ← 40
52	$fp ← M($sp+4) ← M(92) $fp ← 112
56	$sp ← 88 + 12 = 100
60	jr $ra makes: PC ← 40

Return form 1st Call

Addr	What Happens
40	lw $t0, 0($fp); $t0 ← M(112); $t0 ← 2
44	$v0 ← 1x2 $v0 ← $v0 x $t0
48	$ra ← M($sp+8) ← M(108) $ra ← factorial caller RA
52	$fp ← M($sp+4) ← M(104) $fp ← factorial caller FP
56	$sp ← 100 + 12 = 112
60	jr $ra (PC + 4 of fact caller)

10d Undo stack pushes, "restore" $ra, $fp

11 Go back to jal + 4

13a Return as before

14a Calculate next value to return

Memory Contents: (Assume main() calls function which calls factorial.)

Memory Address	Before 1st Fact Call	During 1st Fact Call	During 2nd Fact Call	During 3rd Fact Call	Return from 3rd	Return from 2nd	Return from 1st
76				**Current $sp**			
80				Saved $fp from prior call (100)			
84				Saved $ra of fact (40)			
88			**Current $sp**	**Current $fp** N never stored	**$sp 3rd fact call out**		
92			Saved $fp from prior call (112)				
96			Saved $ra of fact (40)				
100		**Current $sp**	**Current $fp** N = 1			**$sp 2nd fact call out**	
104		Saved $fp of function calling fact (124)					
108		Saved $ra of function calling fact					
112	**Current $sp**	**Current $fp** N = 2					**$sp 1st fact call out**
116	Saved $fp of main						
120	Saved $ra of main						
124	**Current $fp**						

10b More of the same, $ra = 40

10e Pop Stack

1 make room for $sp, $fp, N

13b Pop Stack

8a More of the same, $ra = 40

2 save $ra, $fp (prep for new call)

3 update $fp to define start of call frame

Callee saving

14b Pop Stack; restore address of function that called factorial

0 Main() calls function which calls factorial